

Applications and Implementation

Working Group

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➤ Potential Applications

➤ Astrophysics

➤ rp process: (p, γ)

➤ p process: (γ, n) , (γ, α)

➤ s process: (n, γ)

➤ r process: (n, f) , (n, γ)

➤ Stockpile stewardship

➤ Radiochemical flux monitors: (n, γ) , $(n, 2n)$, (n, p)

➤ Actinides: (n, f) , (n, γ)

➤ Fission fragments: (n, γ) , $(n, 2n)$

➤ ATW, Criticality, etc.

➤ Actinides: (n, xnf)

➤ Nuclear structure

The rp process and (p, γ) reactions

➤ Proton-rich nuclei near the proton drip line

- Novae: $E_p < 2 \text{ MeV}$ & $A < 40$
- X-ray bursts: $E_p < 4 \text{ MeV}$ & $A < 105$

➤ Low level density

- Isolated resonances
- Transfer reactions are well-established technique to resolved states
- Shell model and R-matrix are theoretical workhorses

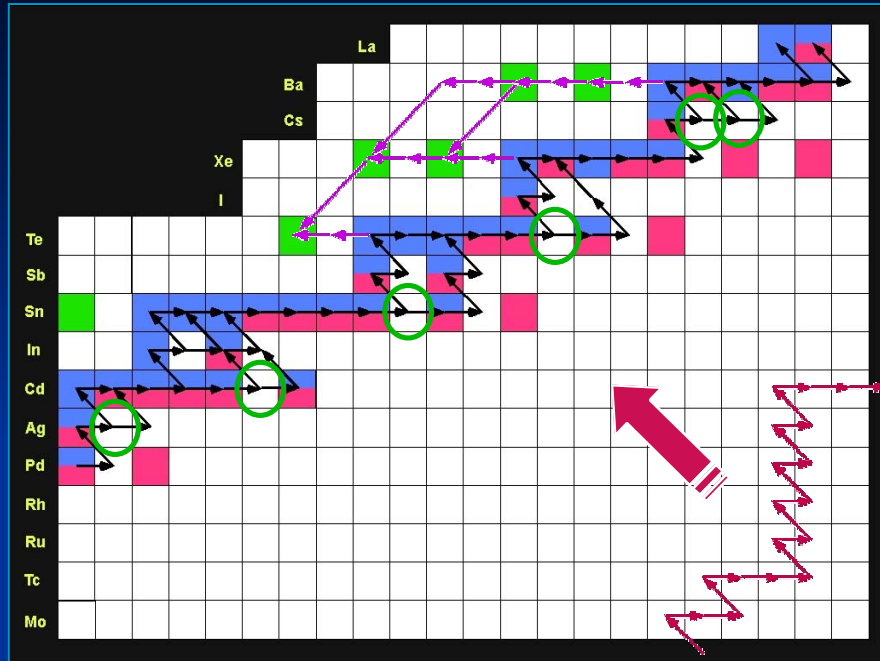
➤ High level density

- HF rates are used
- Detailed comparisons of HF to (p, γ) near stability and shell model rates have been performed
- Can improvements be made in HF rates (e.g. better level densities)? Could measurements of surrogate reactions to unresolved states help?

➤ Intermediate level density

- HF not reliable, but difficult experimentally to resolve experimentally resolve states: e.g. $^{72}\text{Br}(p,\gamma)^{73}\text{Kr}$ $Q=5.1 \text{ MeV}$
- Surrogate reactions may be an important tool for improving reaction rates in this regime

Supernovae



➤ p process

- Low abundance
- Proton-rich nuclei
- ^{74}Se - ^{196}Hg
- (γ, α) and (γ, n)
- Reactions on excited states
- HF rates are used
- Low-energy αN optical model
- (n, α) used ~ other surrogates?

➤ r process

- Masses, half-lives, P_n most important
- Studies of neutron-rich nuclei (structure) important for improving models
- Fission is potentially very important, models only beginning to incorporate.
- Need fission model (probability and mass distribution) with predictive power.
- (n, γ) rates can redistribute matter during freezeout
 - Low level density: Surrogate reactions (e.g. d,p)
 - High level density: HF rates (level densities, isospin & parity dependence)

s process branch points

Isotope	Half-life	RIA intensity (10 ⁹ pps)
⁷⁹ Se	1.1x10 ⁶ y	20
⁸⁵ Kr	10.7 y	80
⁸⁶ Rb	19 d	800
⁸⁹ Sr	50 d	1
⁹⁴ Nb	2x10 ⁴ y	1
¹⁰³ Ru	39 d	1
¹⁰⁶ Ru	367 d	5
¹¹⁰ Ag	250 d	10
¹¹⁵ Cd	44 d	90
¹¹⁴ In	50 d	90
¹²¹ Sn	50 y	120
¹²³ Sn	130 d	150
¹²⁴ Sb	60 d	1
¹²⁵ Sb	2.8 y	3
¹²⁷ Te	109 d	1
¹²⁹ Te	34 d	20
¹³³ Xe	5.2 d	200
¹³⁴ Cs	2.1 y	2000
¹³⁵ Cs	2x10 ⁶ y	3000
¹⁴¹ Ce	33 d	500
¹⁴³ Pr	14 d	800
¹⁴⁷ Nd	11 d	80
¹⁴⁷ Pm	2.62 y	80
¹⁵¹ Sm	90 y	10

Isotope	Half-life	RIA intensity (10 ⁹ pps)
¹⁵³ Sm	1.9 d	20
¹⁵² Eu	13 y	40
¹⁵⁴ Eu	8.6 y	30
¹⁵⁵ Eu	4.9 y	4
¹⁵³ Gd	241.6 d	20
¹⁶⁰ Tb	72 d	1
¹⁶³ Ho	4570 y	400
¹⁶⁹ Er	9.4 d	30
¹⁷⁰ Tm	128.6 d	100
¹⁷¹ Tm	1.92 y	100
¹⁷⁷ Lu	6.7 d	1
¹⁷⁹ Ta	1.7 y	1
¹⁸¹ Hf	42 d	30
¹⁸² Hf	9x10 ⁶ y	10
¹⁸² Ta	114 d	1
¹⁸⁵ W	75.1 d	2
¹⁸⁶ Re	2.0 y	1
¹⁹¹ Os	15 d	2
¹⁹² Ir	74 d	1
¹⁹³ Pt	50 y	1
¹⁹⁸ Au	2.7 d	1
²⁰³ Hg	47 d	100
²⁰⁴ Tl	3.77 y	1
²⁰⁵ Pb	1.5x10 ⁷ y	1

➤(n,γ) MACs

➤8 and 30 keV

➤Branch points (radioactive!) extremely important

➤DANCE will measure some ~ but *very* difficult

➤Alternate technique (surrogate reaction) needed

➤One would like accurate (10%) measurements

Stockpile stewardship needs

➤ Radiochemical tracers

➤ Ti, Cr, Fe, Br, Kr, Y, Zr, Nb, Mo, Tm, Lu, Ta, Ir, Au, Bi

➤ Actinides

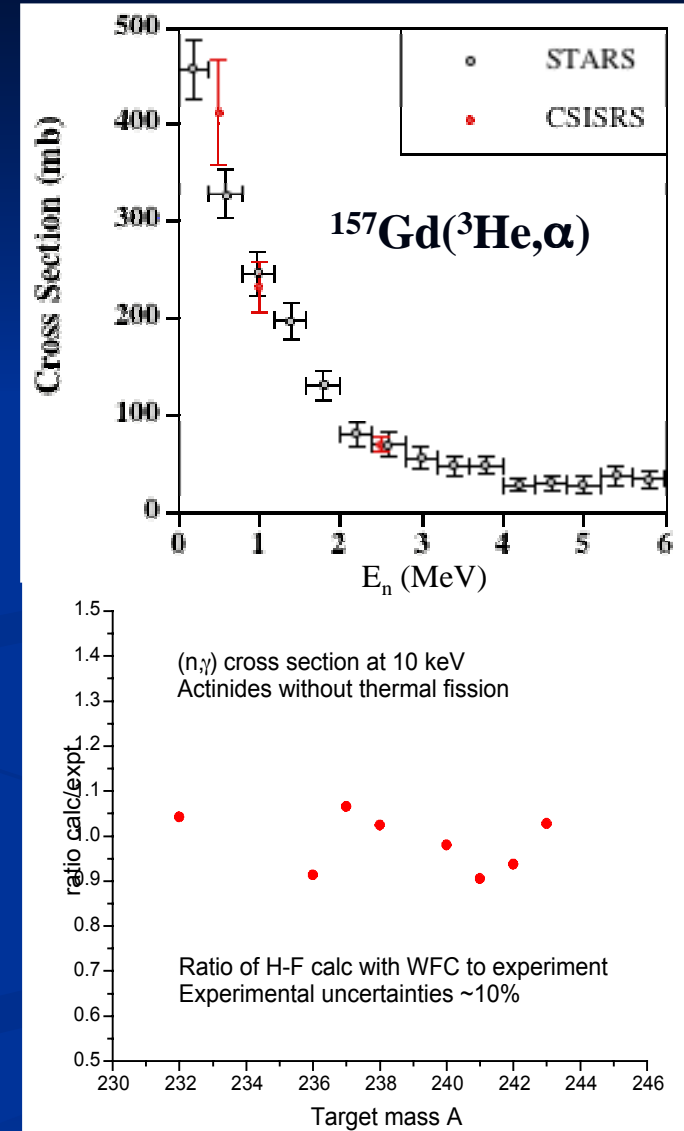
➤ Prompt fission fragments

➤ Sensitivity studies with reaction rate networks may help set priorities

Reaction	Energy Range (MeV)	Importance	Accuracy
(n,γ)	0.01- 0.2	High	10%
(n,n')	1-10	Low	10%
(n,2n)	10-16	High	3-5%
(n,pX), (n,α)	0.1-16	Medium	10%
(n,f)	0.1-16	High	1-2%

Low energy (n, γ)

- Very important for both stewardship science and the s process
- Presentations by Bernstein, Dietrich are encouraging, but much work to do
- Challenges:
 - Need to probe narrow energy window near the neutron threshold
 - Energy resolution \gg level spacing
 - What energy resolution is required?
 - Need to characterize detector response function accurately.
- Need to thoroughly investigate test cases on lighter nuclei
- Is there useful existing data?



Test cases

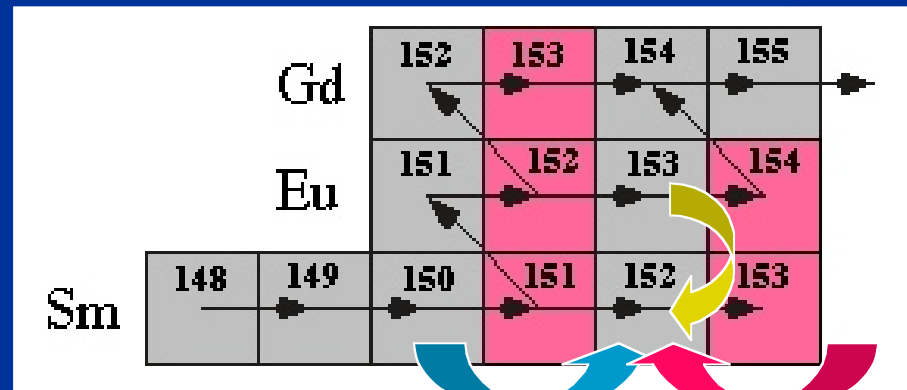
- How much meaning can be inferred from a test case?
- A variety of test cases with different dependences is desirable.
- How problematic is angular momentum matching? Do angular distributions help in constraining the J^π distribution in the compound nucleus?
- How much can measuring multiple channels help?

$^{151}\text{Sm}(n,\gamma)$

➤ Important s process branch point

➤ (n,γ) will be measured

➤ $S_n = 8.3 \text{ MeV}$



➤ $^{152}\text{Sm}(p,p')$

➤ $^{154}\text{Sm}(p,t)$

➤ $^{150}\text{Sm}(t,p)$

➤ $^{153}\text{Eu}(t,\alpha)$

$(n, xn \ y p \ z\alpha)$ needs

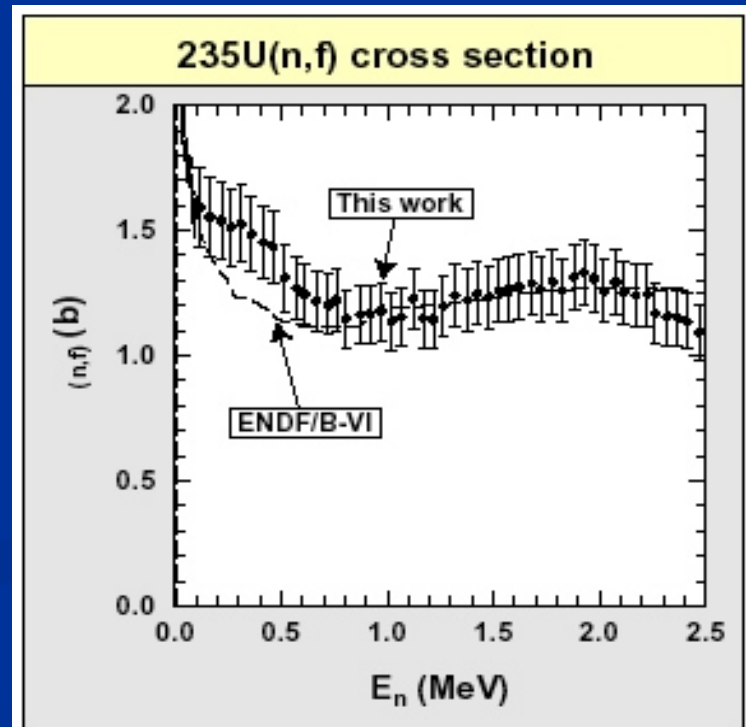
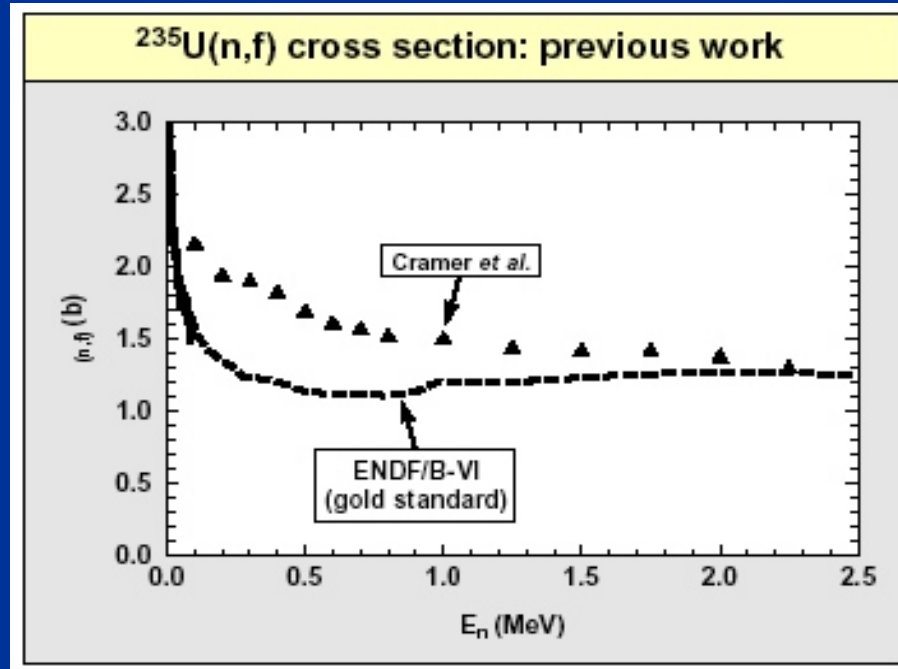
- High accuracy (3-5%) desired
 - But we'll take what we can get
- Energies are typically 5-15 MeV
- Only moderate energy resolution (100 keV) required
- Most interesting cases are when several channels are competing for the reaction cross section
 - Fission & (n, n') & $(n, 2n)$
 - (n, n') & (n, p) & $(n, 2n)$

(n, xn yp z α) issues

- Helps to constrain the reaction cross section
 - How good is a global optical model?
 - What measurements can improve?
- How do you identify the channel of interest.
 - Gammas are positive but can you understand cascade scheme?
 - Neutrons more direct? Gd-doped scintillators?
- Contributions from direct reactions, pre-equilibrium
 - Particle distributions give us a probe
- Higher beam energies required to populate equivalent 5-14 MeV neutrons compared with (n, γ)

Neutron-induced fission

- General consensus: Walid's talk was an example to live up to
 - Comparisons with solid benchmarks from direct measurements
 - Addressed angular momentum matching issues
- New issues at higher energies (pre-equilibrium, more reliance on models) - limitations still to be explored
- (n,xnf) at high energies of interest for ATW, criticality, etc.



Conclusions and general comments

- There are significant nuclear data needs not met by direct measurement.
- Surrogate techniques seem promising for obtaining some of this data.
- A substantial body of test cases needs to be measured and evaluated to build confidence in the applicability and precision.
 - Results will depend on mass region, shell structure, level density. Test cases need to be matched to nuclei of interest.
- Where are we going to do these measurements?
 - Can sufficient beam time and manpower be devoted to this effort?
 - Throughput?
- How much information is to be gained from previous work?
 - Important to capitalize on the lessons learned from the substantial work in previous decades, ala Walid.
- Can significant improvements be made in model inputs?
 - Level densities
 - Isospin dependences
 - Parity dependences
- Can studying surrogate reactions help improve the predictive power of theory where there is no data?